Primordial Black Holes as a dark matter candidate

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- Motivation

- PBH formation

- PBH abundance constraints

Motivation

Cosmological observations indicate that dark matter (DM) has to be cold and non-baryonic.

Primordial Black Holes (PBHs) are black holes that form in the early Universe and are therefore non-baryonic.

Lifetime longer than the age of the Universe for $M > 10^{15}$ g.

A DM candidate which (unlike WIMPs, axions, sterile neutrinos,…) isn't a new particle (however their formation does usually require Beyond the Standard Model physics).

LIGO has detected gravitational waves from mergers of ~30 M_{sun} BHs. Could be formed by astrophysical processes (but a large population of such objects was a bit unexpected).

Could PBHs be the CDM? (and potentially also the source of the GW events??)

Collapse of large density perturbations[$]

During radiation domination an initially large (at horizon entry) density perturbation can collapse to form a PBH with mass of order the horizon mass. Zeldovich & Novikov; Hawking; Carr & Hawking

For gravity to overcome pressure forces resisting collapse, size of region at maximum expansion must be larger than Jean's length.

Simple analysis:

density contrast: $$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$ equation of state: $$p = \gamma \rho$$

threshold for PBH formation: $$\delta \geq \delta_{\rm c} \approx \gamma = \frac{1}{3}$$

PBH mass: $$M \approx \gamma M_{\rm H}$$ $$M_{\rm H} \sim 10^{15}\,{\rm g} \left(\frac{t}{10^{-23}\,{\rm s}} \right)$$

$ Other formation mechanisms include collapse of cosmic string loops and bubble collisions.

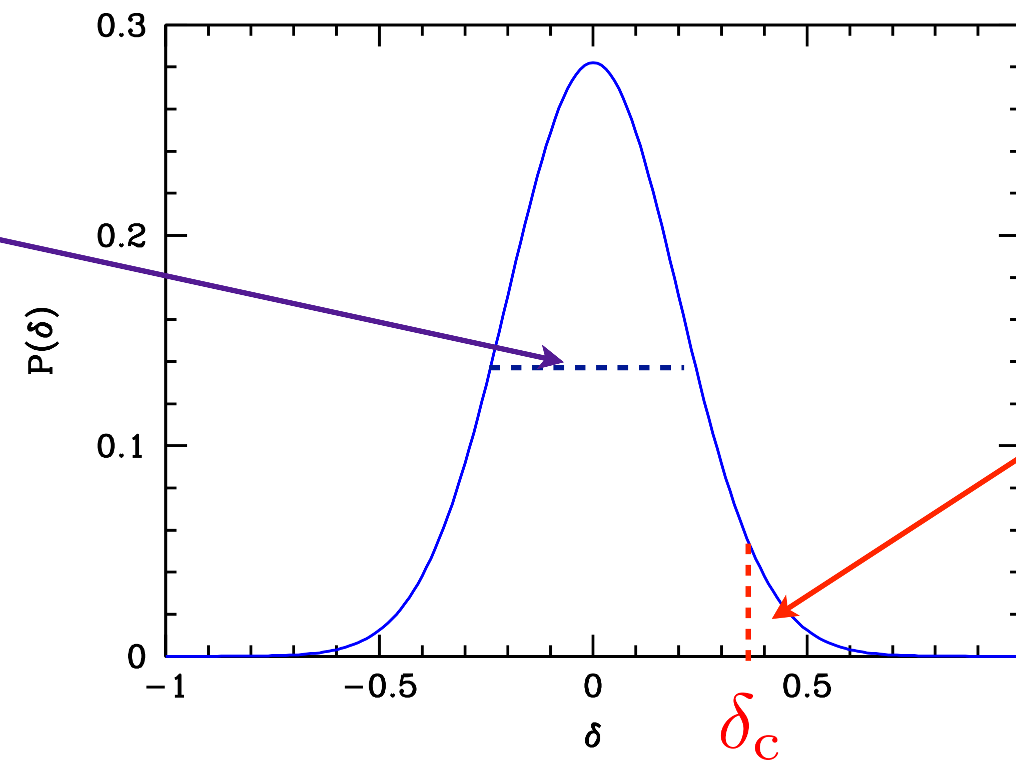
initial PBHs mass fraction (fraction of universe in regions dense enough to form PBHs):

$$\beta(M) \sim \int_{\delta_c}^{\infty} P(\delta(M_H))\, d\delta(M_H)$$

assuming a gaussian probability distribution:

$$\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$$

$\sigma(M_H)$ (mass variance)
typical size of fluctuations



PBH forming fluctuations

If $\sigma(M_H)$ is independent of mass, PBHs have an extended mass function Carr.

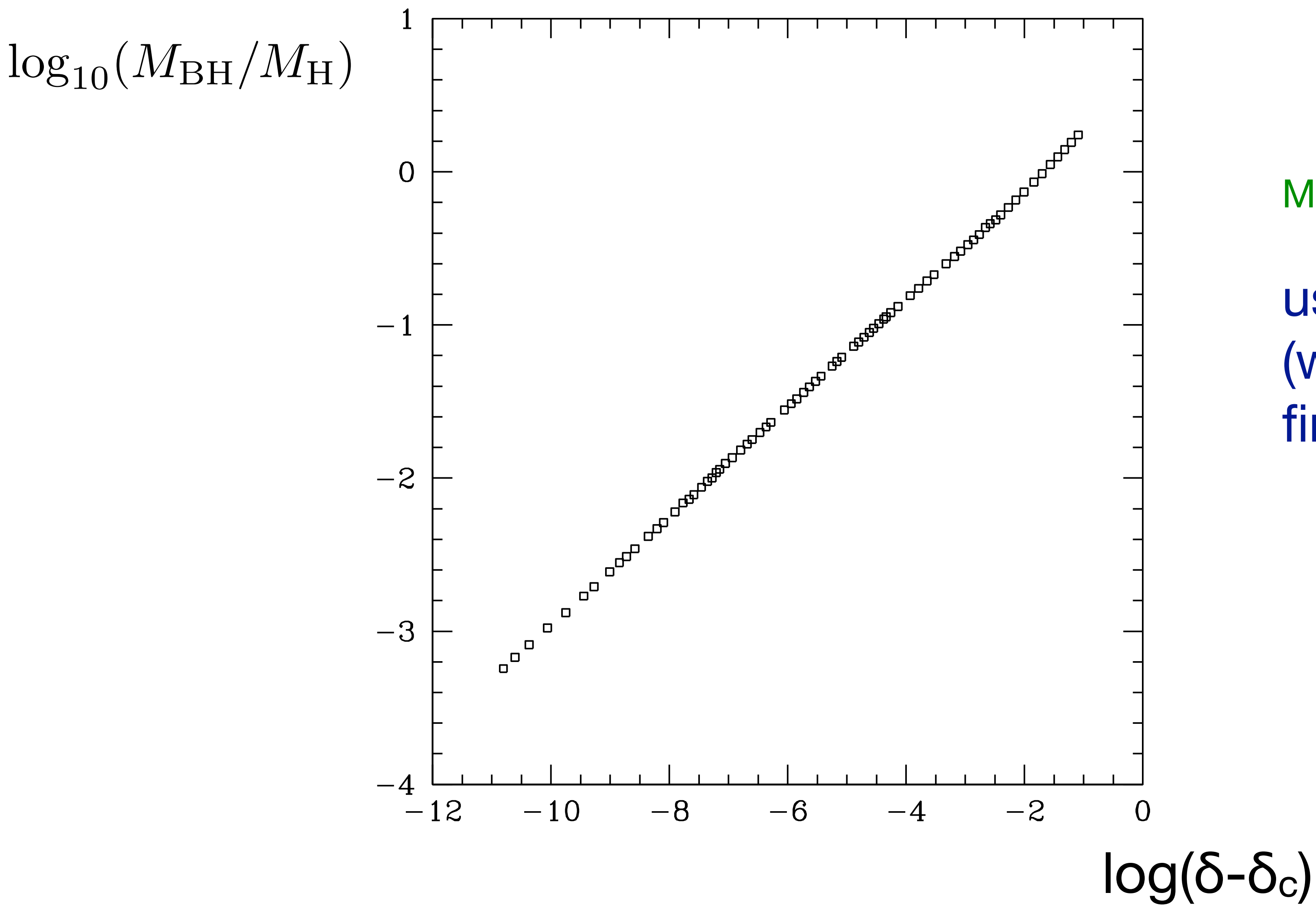
Otherwise most PBHs form on scale(s) where perturbations are largest.

Critical phenomena

Choptuik; Evans & Coleman; Niemeyer & Jedamzik

BH mass depends on size of fluctuation it forms from:

$$M = kM_{\mathrm{H}}(\delta - \delta_{\mathrm{c}})^{\gamma}$$



Musco, Miller & Polnarev

using numerical simulations (with appropriate initial conditions) find k=4.02, γ=0.357

Get PBHs with range of masses produced even if they all form at the same time.

PBH abundance

Since PBHs are matter, during radiation domination the fraction of energy in PBHs grows with time.

Relationship between PBH initial mass fraction, β, and fraction of DM in form of PBHs, f:

$$\beta(M) \sim 10^{-9} f \left(\frac{M}{M_{\odot}} \right)^{1/2}$$

i.e. initial mass fraction must be small, but non-negligible.

On CMB scales the primordial perturbations have amplitude $\sigma(M_{\rm H}) \sim 10^{-5}$

If the primordial perturbations are close to scale-invariant the number of PBHs formed will be completely negligible:

$$\beta(M) \sim \mathrm{erfc}(10^5) \sim 10^5 \exp\left[-(10^5)^2 \right]$$

To form an interesting number of PBHs need the primordial perturbations to be significantly larger ($\sigma(M_H) \sim 0.01$) on small scales than on cosmological scales.

n.b. inflation does not typically produce a primordial power spectrum which is a pure power law over a wide range of scales.

Inflation: a crash course

A postulated period of accelerated expansion in the early Universe.

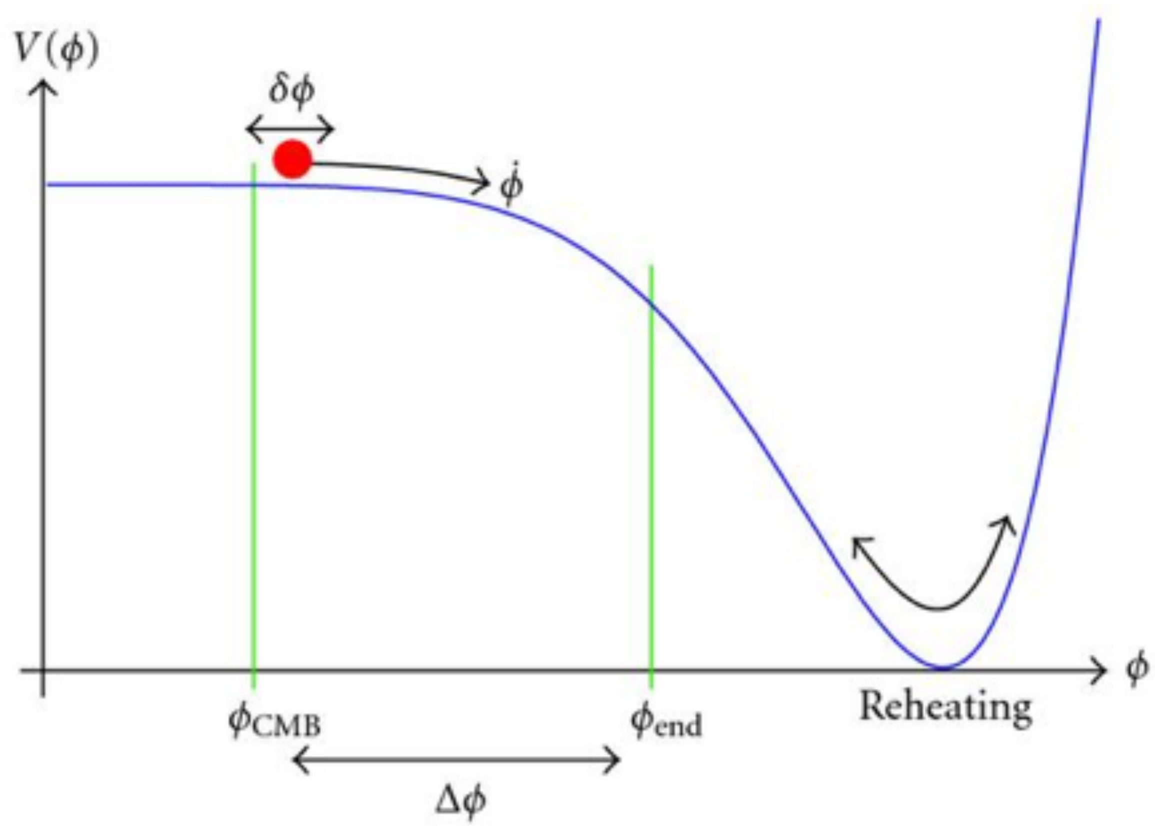
Proposed to solve various problems with the Big Bang (flatness, horizon & monopole).

Driven by a 'slowly rolling' scalar field.

Quantum fluctuations in scalar field generate primordial density perturbations.

Scale dependence of primordial perturbations depends on shape of potential:

$$\sigma^2(M_{\rm H}) \propto \frac{V^3}{(V')^2}$$



Yadav & Wandelt

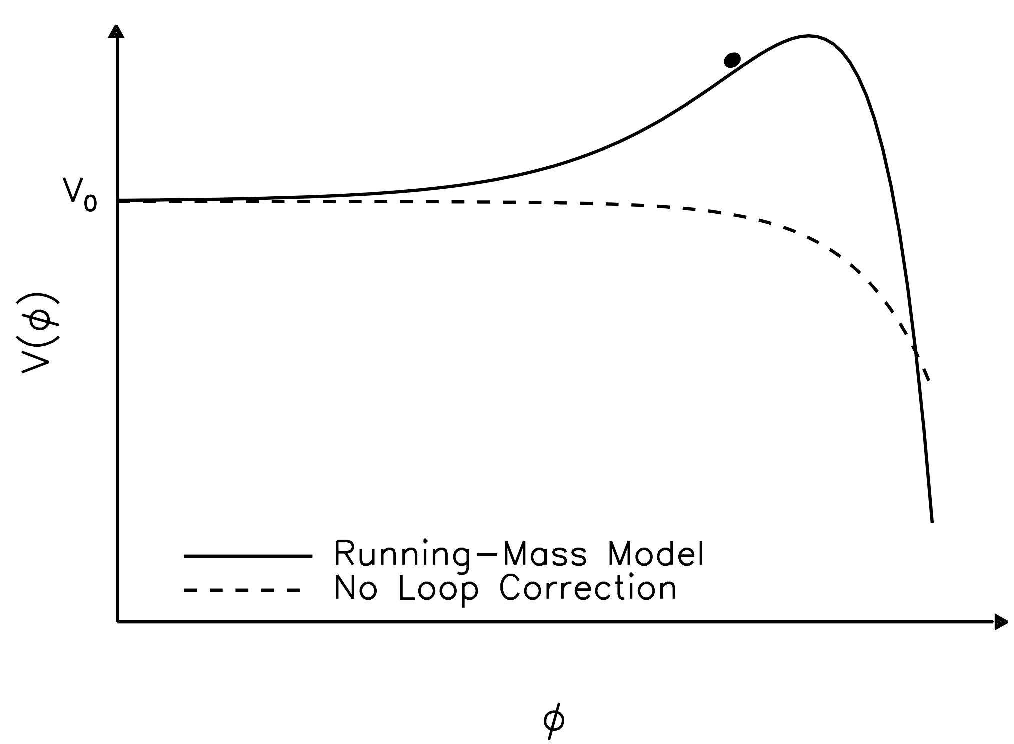
Inflation models with (potentially) large perturbations on small scales

i) Monotonically increasing power spectrum

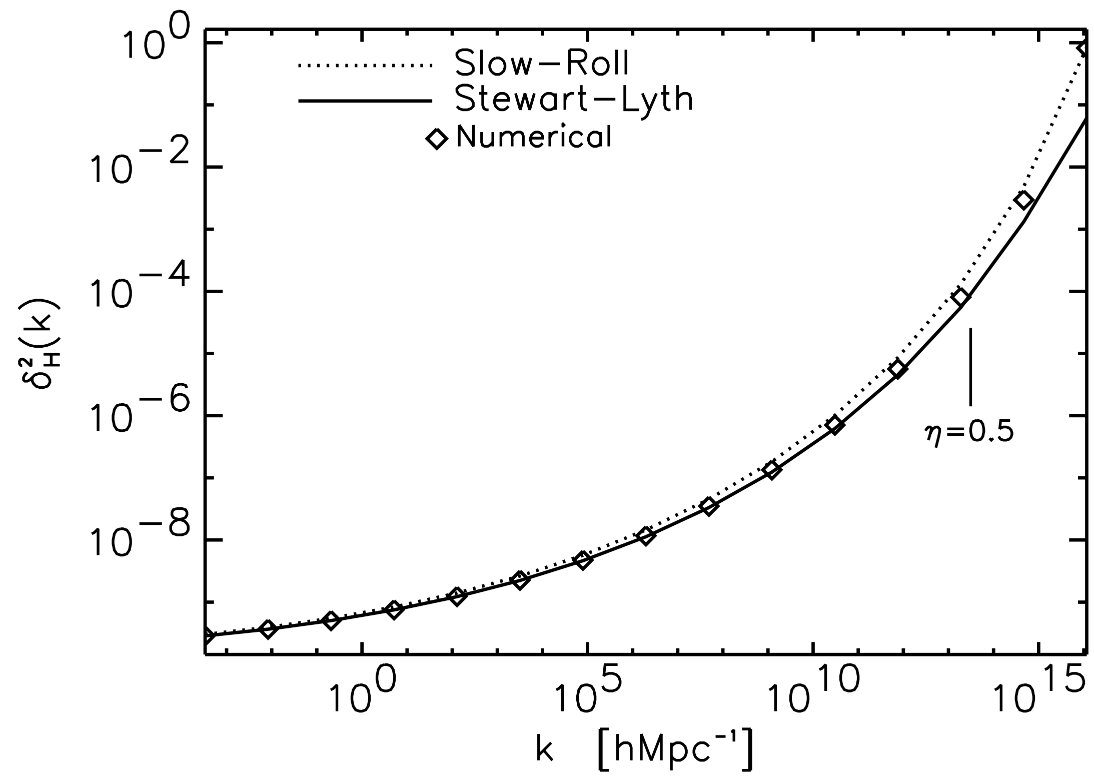
e.g. running-mass inflation Stewart

$$V(\phi) = V_0 + \frac{1}{2} m_\phi^2(\phi)\phi^2$$

potential



primordial power spectrum



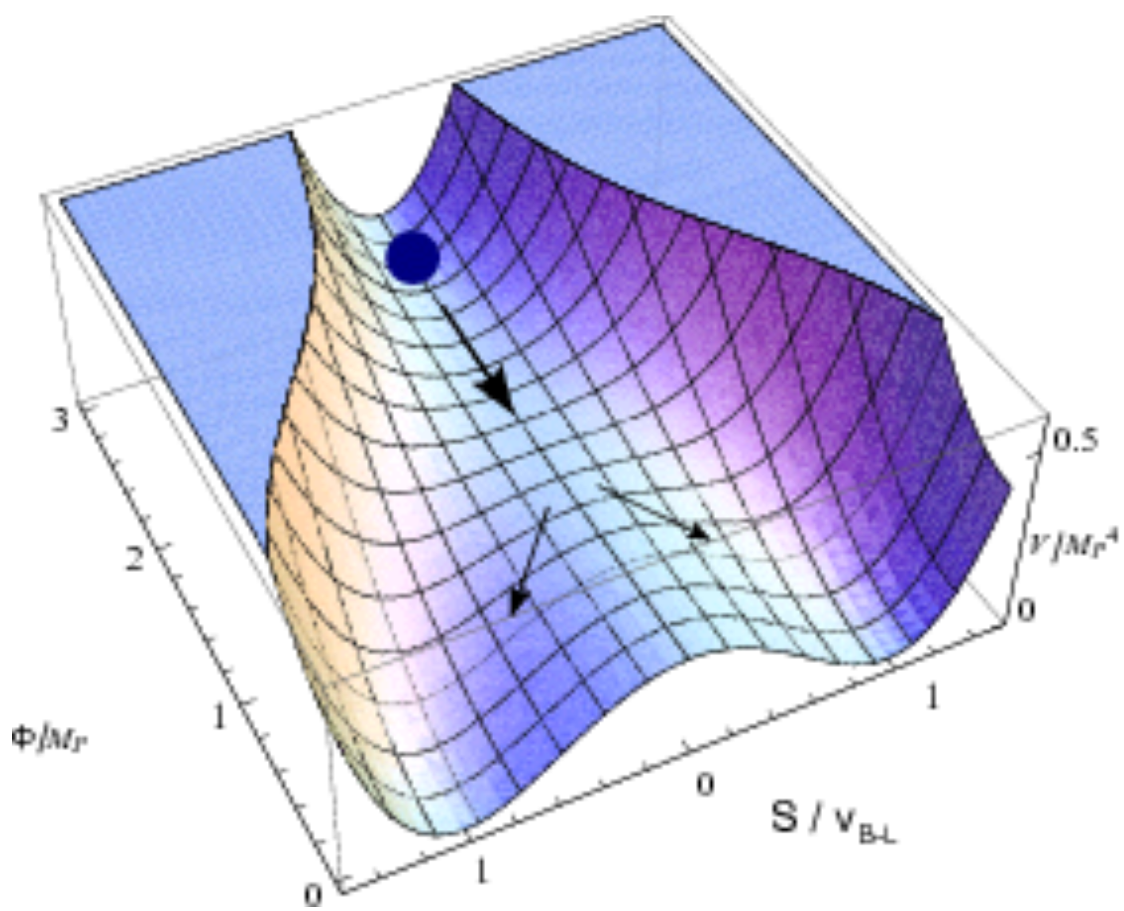
Leach, Grivell, Liddle

ii) models with a feature in the power spectrum

From models with two fields or two periods of inflation or features in the potential.

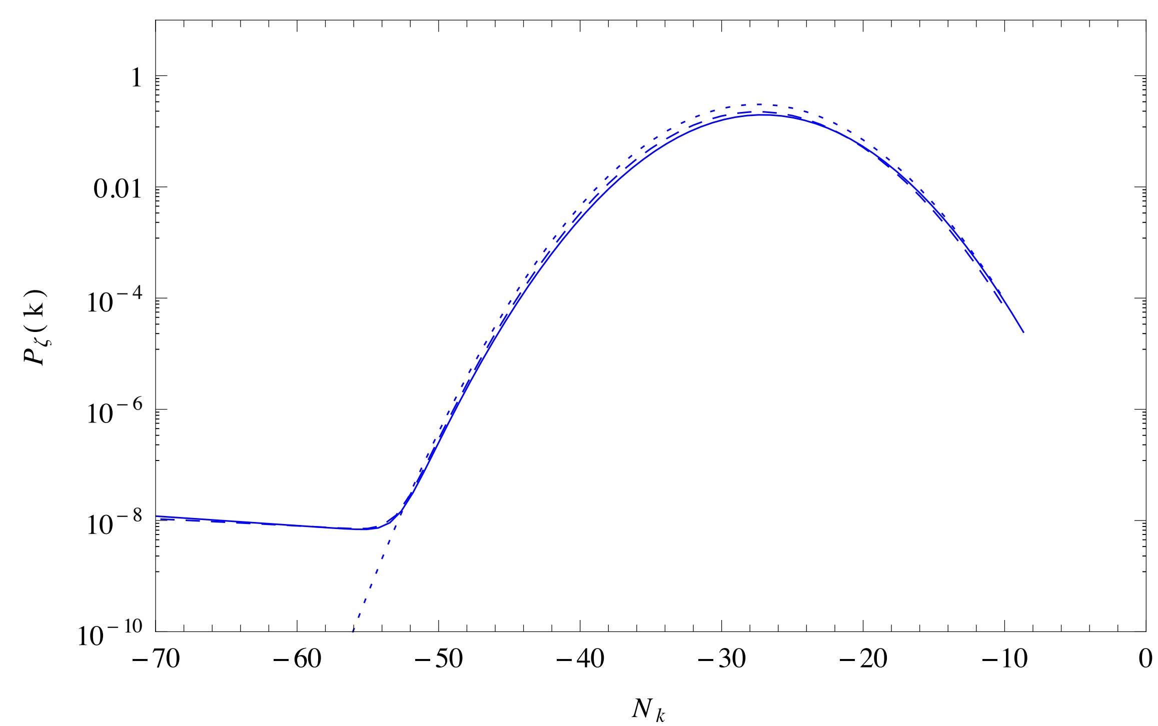
e.g. hybrid inflation with a mild waterfall transition

potential



Buchmuller

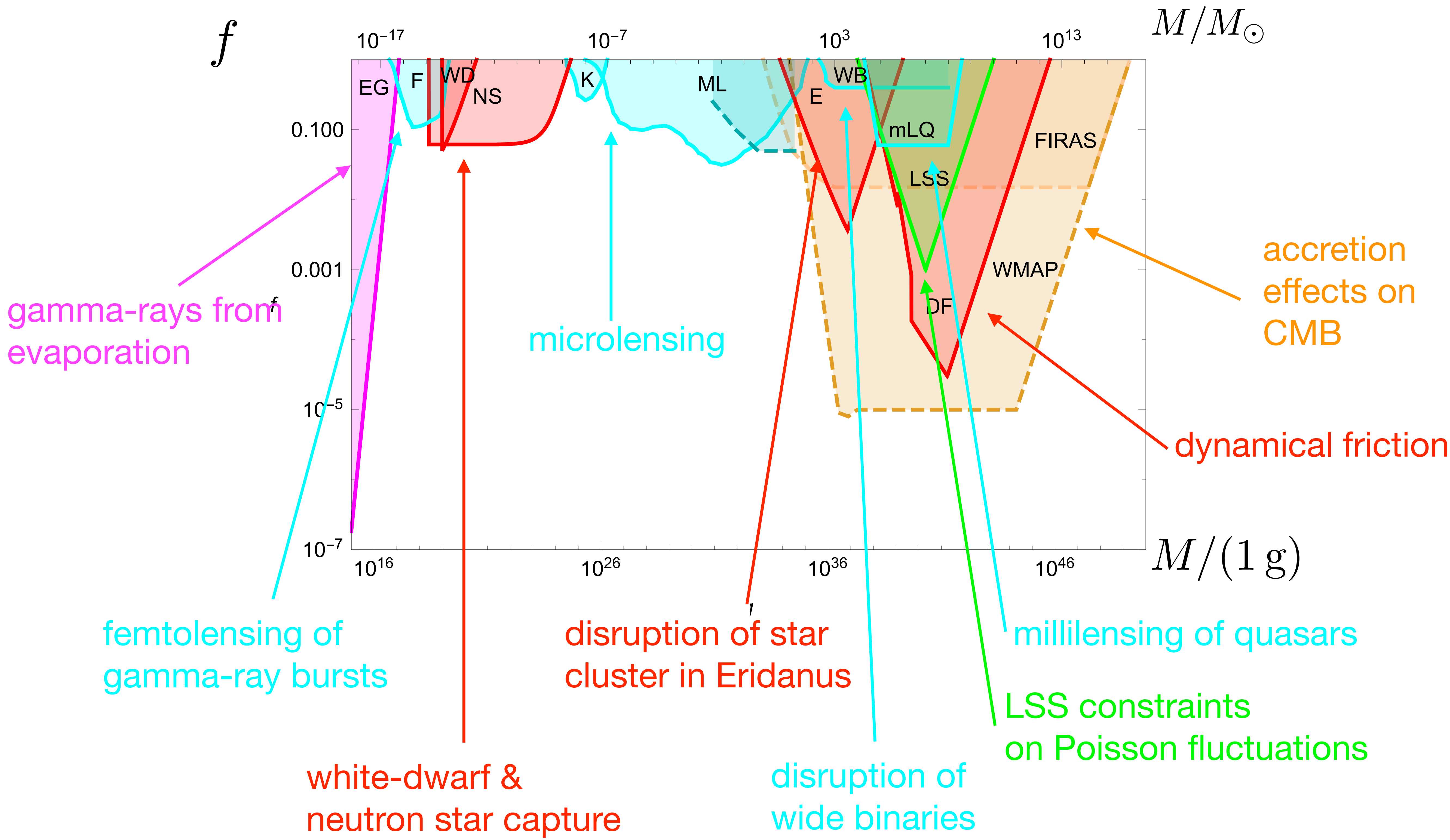
primordial power spectrum



Classe & Garcia-Bellido

PBH abundance constraints

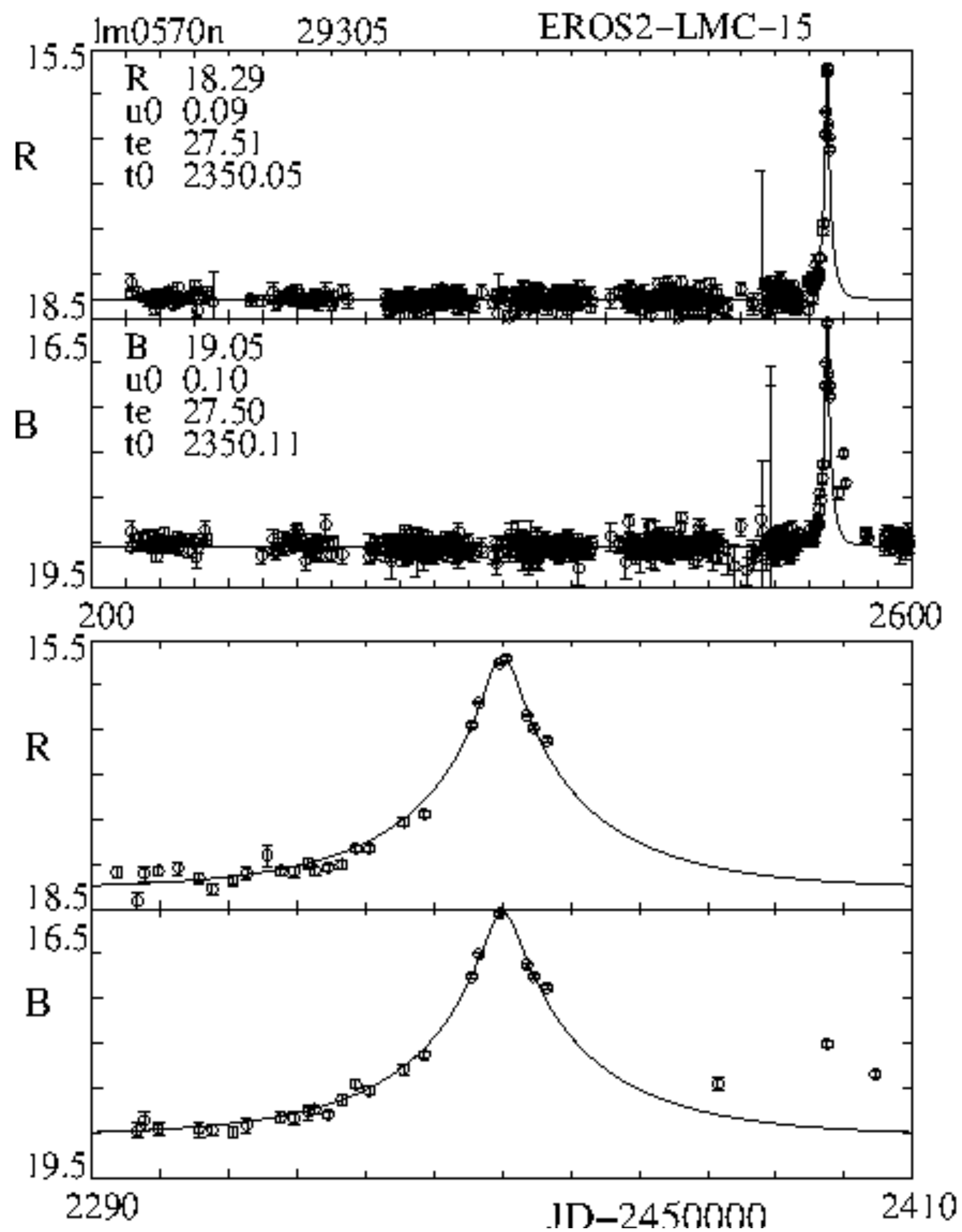
Constraints on PBH halo fraction, f, as a function of PBH Mass: Carr, Kuhnel & Sandstad, see also Carr, Kohri, Sendouda & Yokoyama



Constraints which apply in multi-Solar mass region

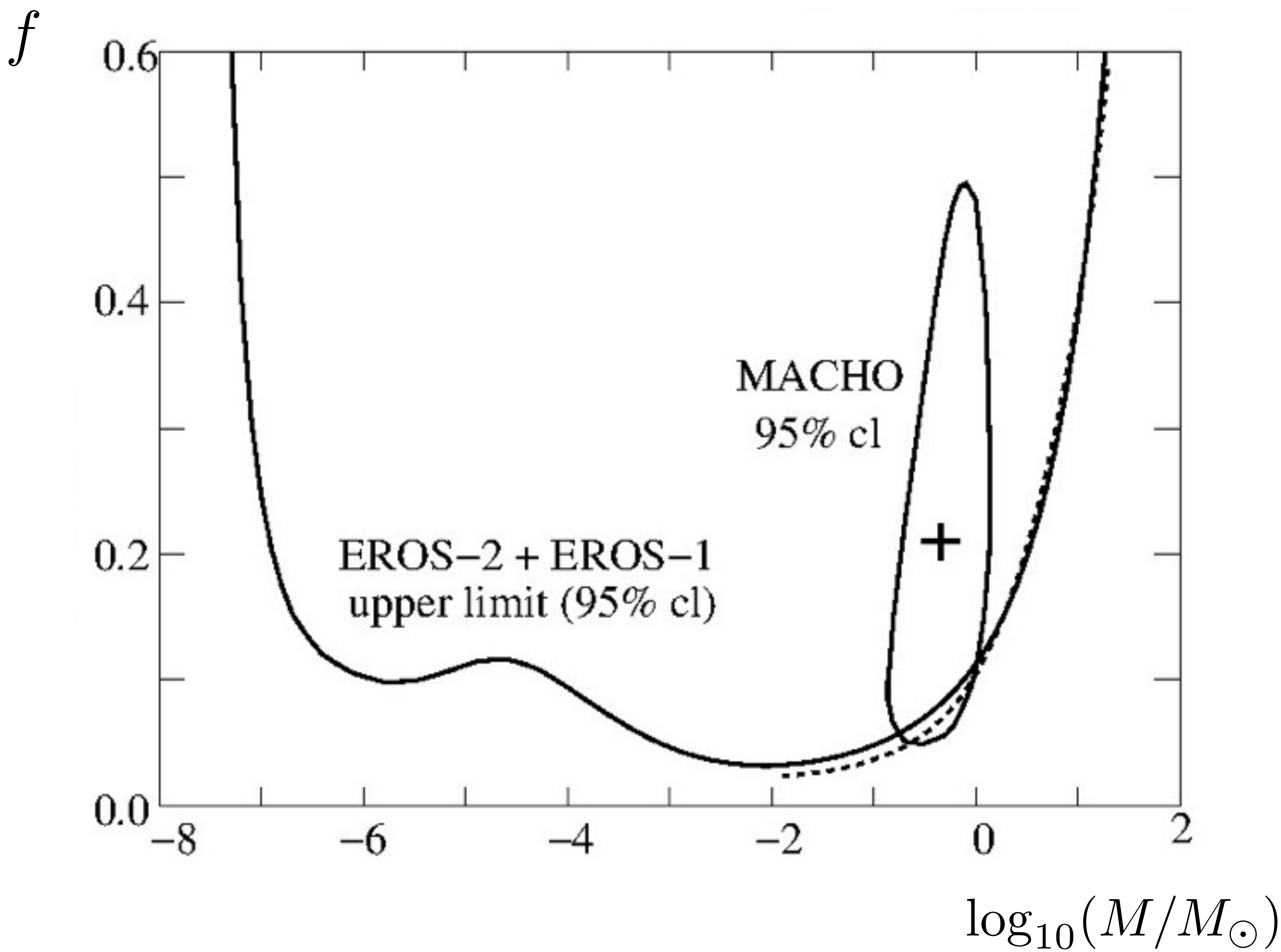
Microlensing

Temporary (achromatic) brightening of background star when compact object passes close to the line of sight.



EROS

EROS constraints on fraction of halo in compact objects, f, **assuming a delta-function mass function:**



EROS

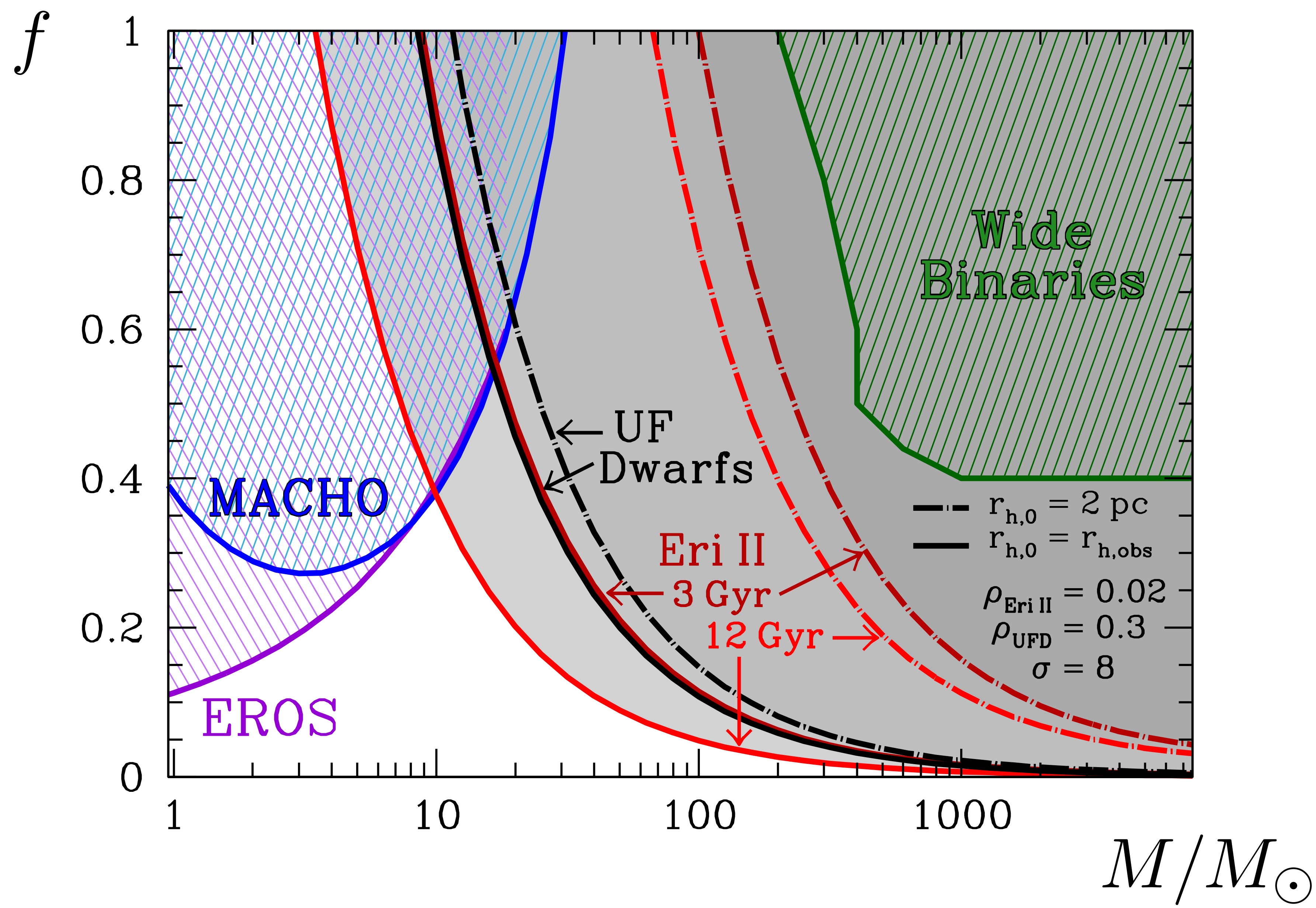
Ultra-faint dwarf heating

Brandt

Compact objects can heat, and cause the expansion of,

i) star clusters within dwarf galaxies (e.g. star cluster at centre of Eridanus II)

ii) ultra-faint dwarf galaxies



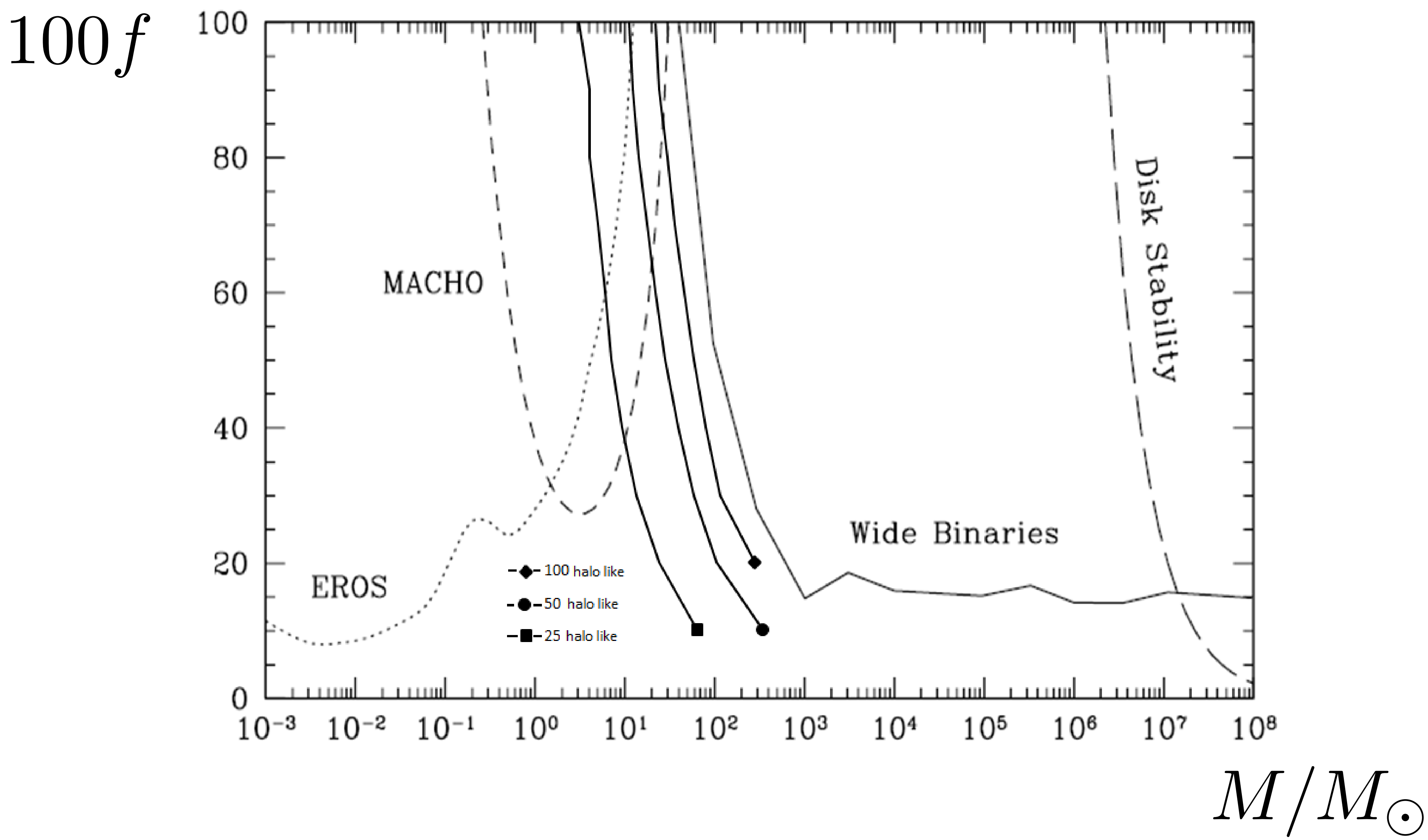
Wide binary disruption

Change & Gould; Yoo, Chaname & Gould; Quinn et al.; Monroy-Rodriguez & Allen

Massive compact objects perturb affect the orbits of wide binaries.

Need to make assumptions about initial distribution of orbits of binaries.

Constraints depend on which subset of binaries are used.

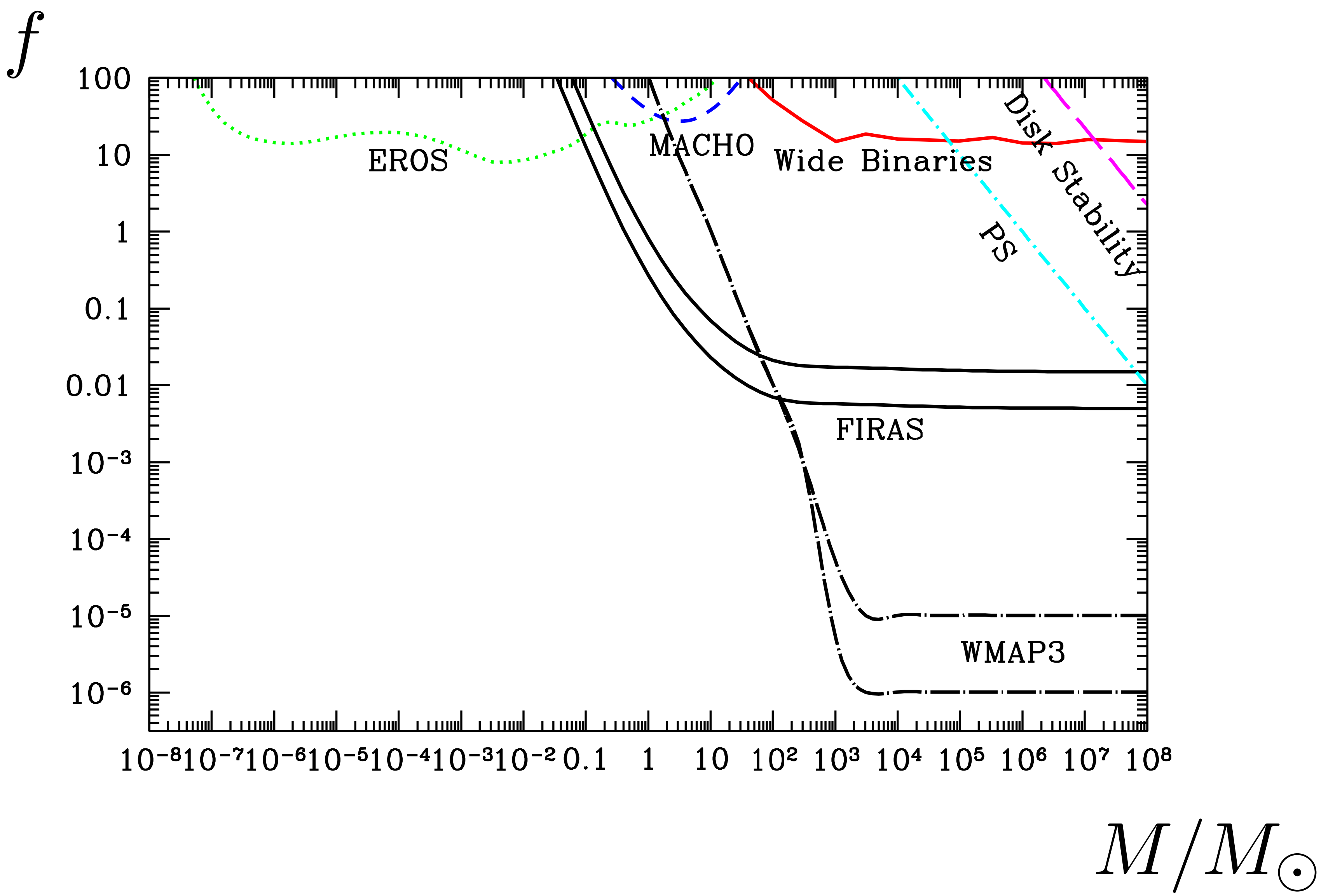


<u>Cosmic Microwave Background distortions</u>

Ricotti et al.

Accretion onto PBH leads to emission of X-rays which can distort the spectrum (FIRAS) and anisotropies (WMAP) in the CMB.

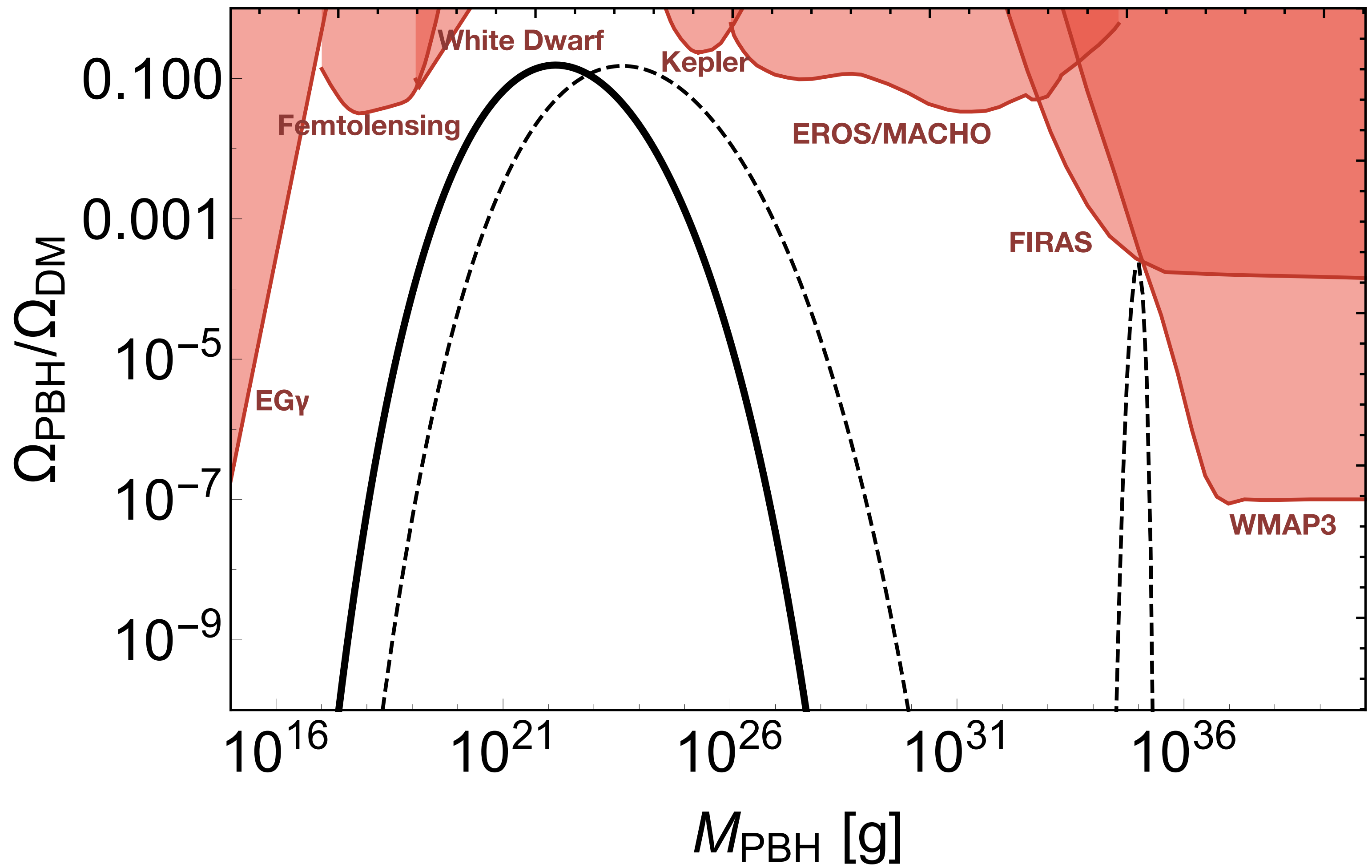
Significant uncertainties in constraint due to modelling of complex astrophysical processes??



PBHs with an extended mass function

Applying constraints calculated assuming a DF MF to extended MFs is subtle.

Can't just compare df/dM to constraints on f as a function of M e.g. arXiv: 1606.07631:



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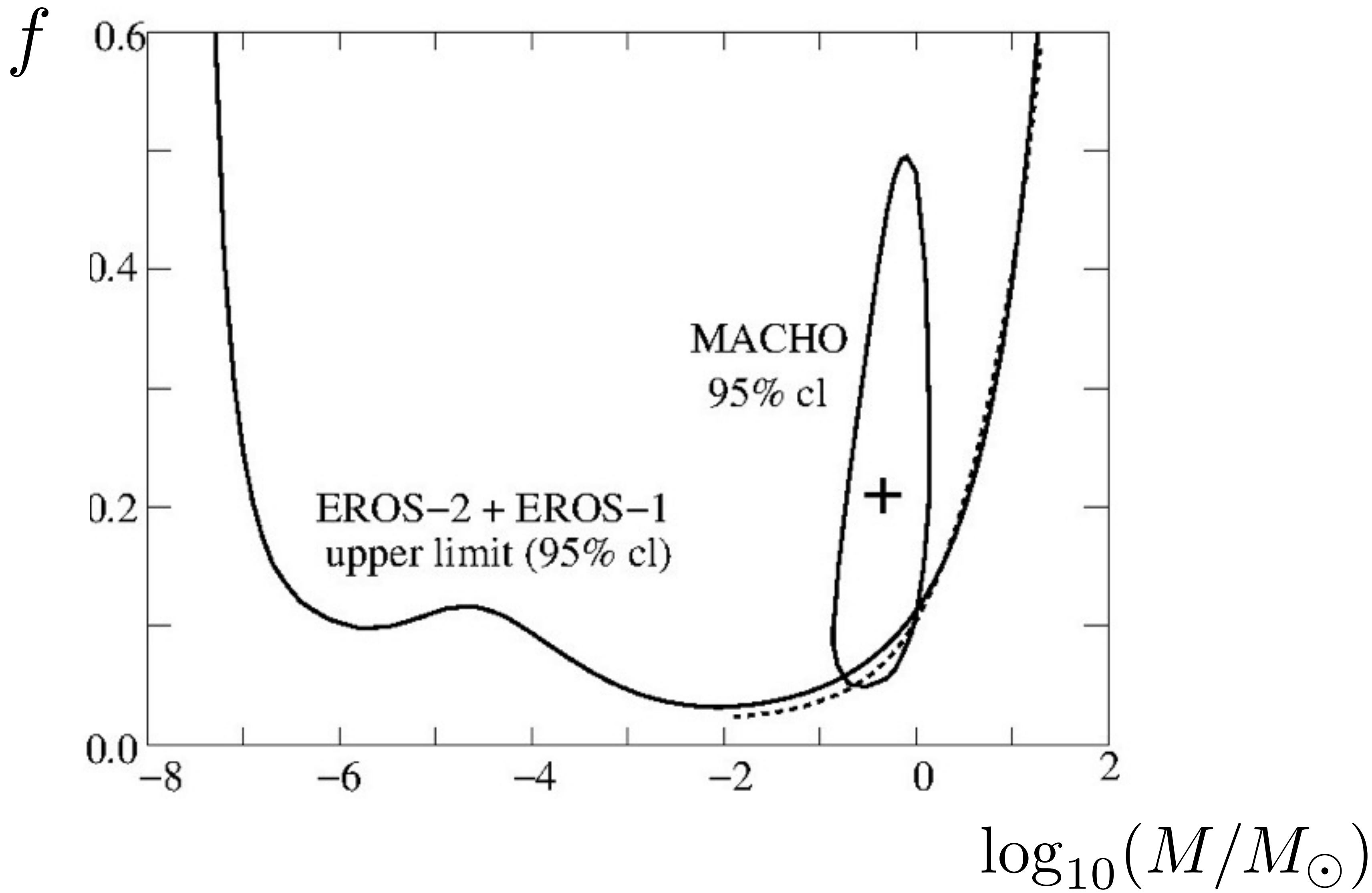


Beware double counting. For instance EROS microlensing constraints allow $f \sim 0.2$ for $M \sim 5\,M_{sun}$ or $f \sim 0.4$ for $M \sim 5\,M_{sun}$, **but NOT BOTH**.

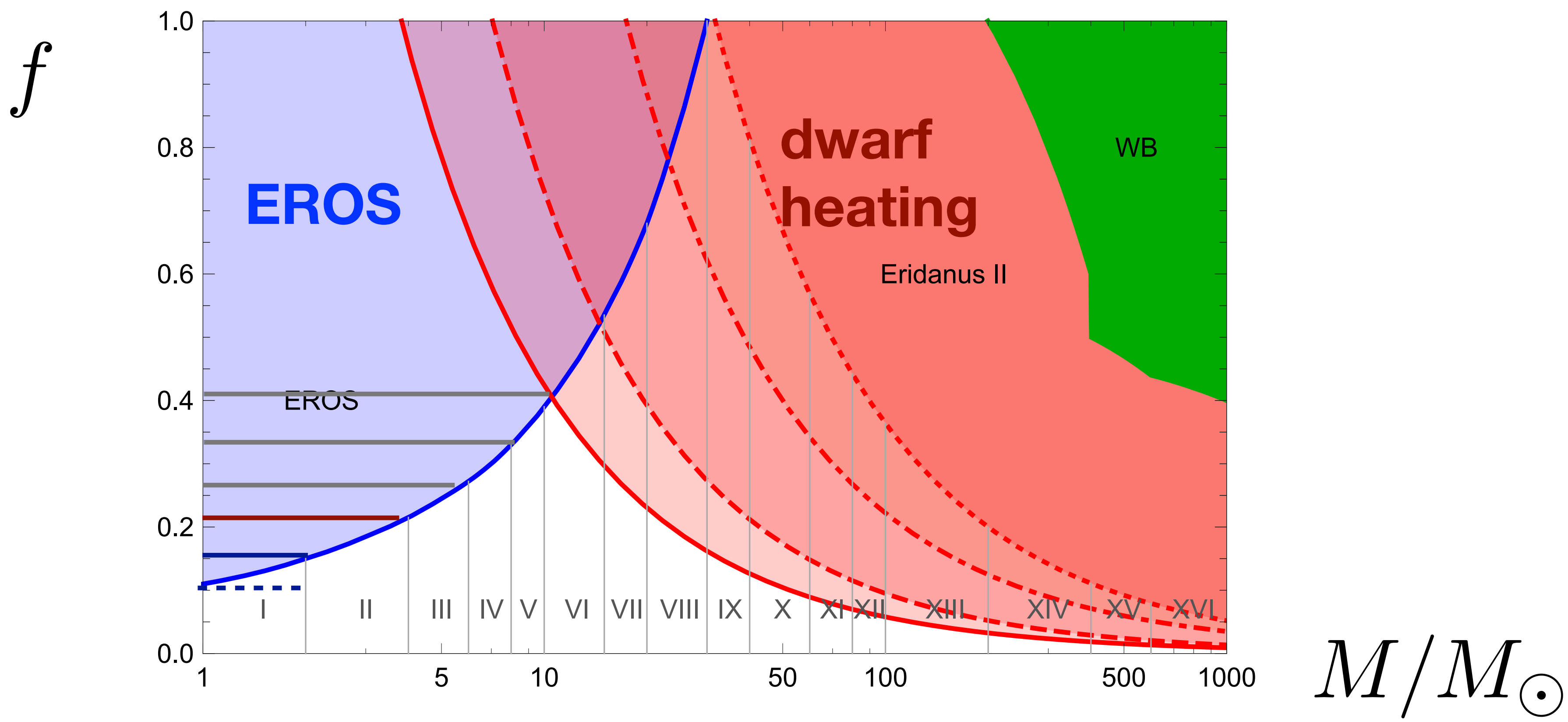
Carr, Kuhnel & Sandstad method:

Divide relevant mass range into bins, I, II, III etc.

Check integral of MF in bin I is less than ***weakest*** limit on f in this bin.

Check integral of MG in bins I+II is less than ***weakest*** limit on f in these bins.

And so on…



This underestimates the strength of the constraints.

If the integral of the MF exceeds weakest limit on f it's definitely excluded, but some which don't are also excluded.

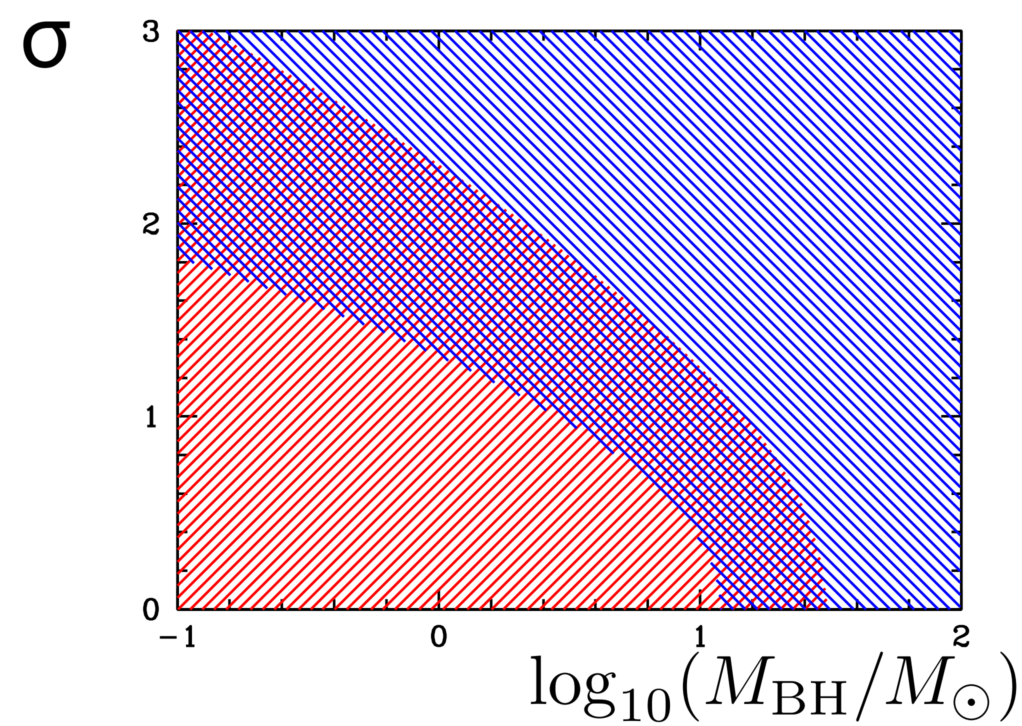
(Conversely all MFs which don't exceed *tightest* limit are definitely allowed, but some which do are also allowed.)

To ascertain for certain whether or not an extended MF is allowed need to explicitly recalculate constraints.

Constraints on the central mass, M_c, and width, σ, of log-normal MF:

Excluded by EROS microlensing data.

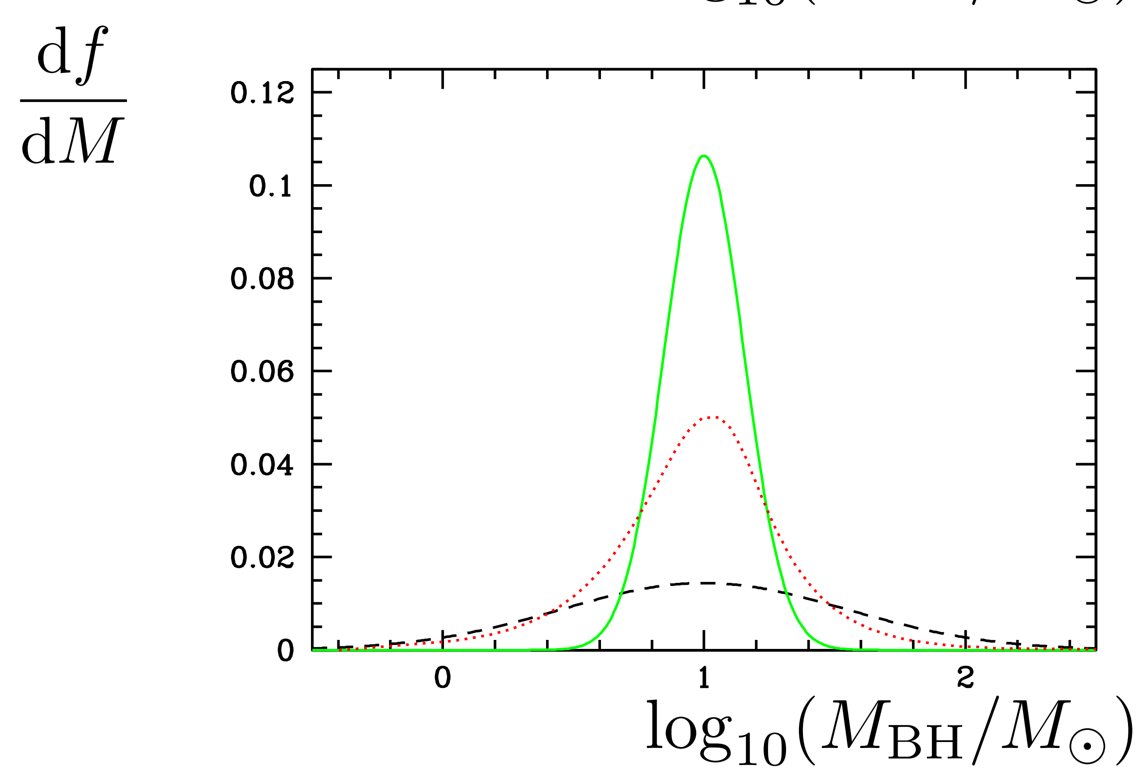
Excluded by heating of ultra-faint dwarfs.



Broadest MF which satisfies the ultra-faint dwarf constraint.

Narrowest MF which satisfies the microlensing constraints.

(axion-curvaton MF from Carr et al.)



Together the microlensing & dynamical constraints exclude (unclustered) multi-Solar mass PBH making up all of the DM (even with an extended MF).

Summary

Primordial Black Holes are a potential non-baryonic cold dark matter candidate.

Various tight constraints on their abundance, but potentially some allowed mass windows remain: 'sub lunar' (10^{20}-10^{24}g) and multi-Solar mass.

PBHs can form from the collapse of large primordial density perturbations. But perturbations need to be larger than on cosmological scales.

Need to tune both wavenumber(s) on which perturbations are large (to produce PBHs in an allowed mass window) and amplitude (to produce correct abundance).

Due to critical collapse the PBHs have an extended MF, even if they all form at the same time/scale.

Applying constraints to extended MFs is subtle: for definitive conclusions need to explicitly recalculate the constraints.

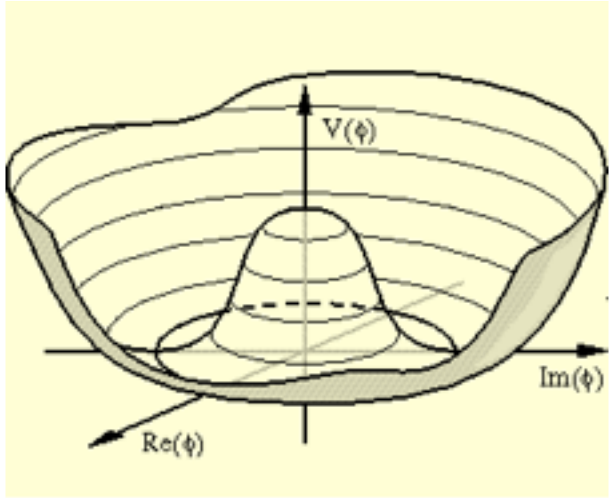
Together microlensing and dynamical constraints exclude multi-Solar mass PBHs making up all of the DM, even with an extended mass function.

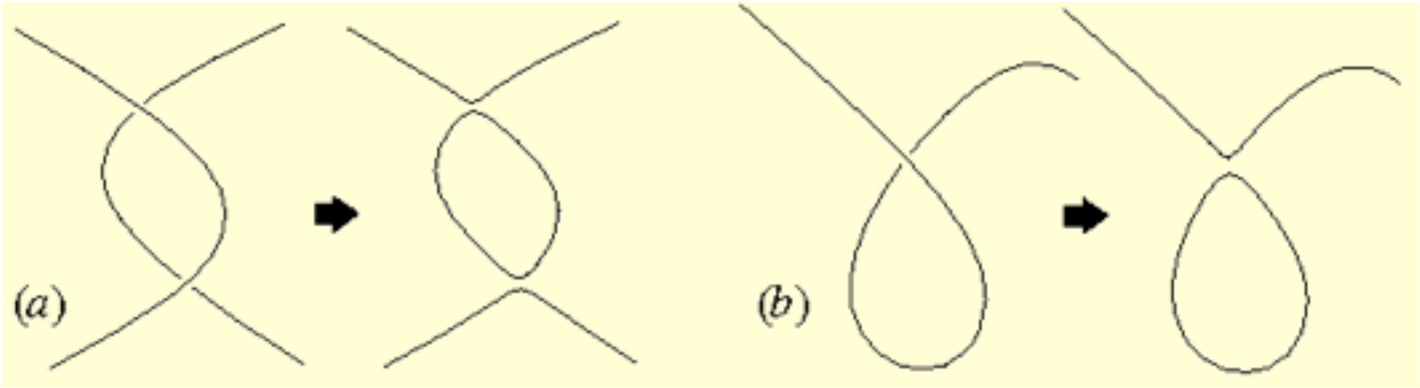
Other mechanisms

Collapse of cosmic string loops
Hawking; Polnarev & Zemboricz;

Cosmic strings are 1d topological defects formed during symmetry breaking phase transition.

String intercommute producing loops.



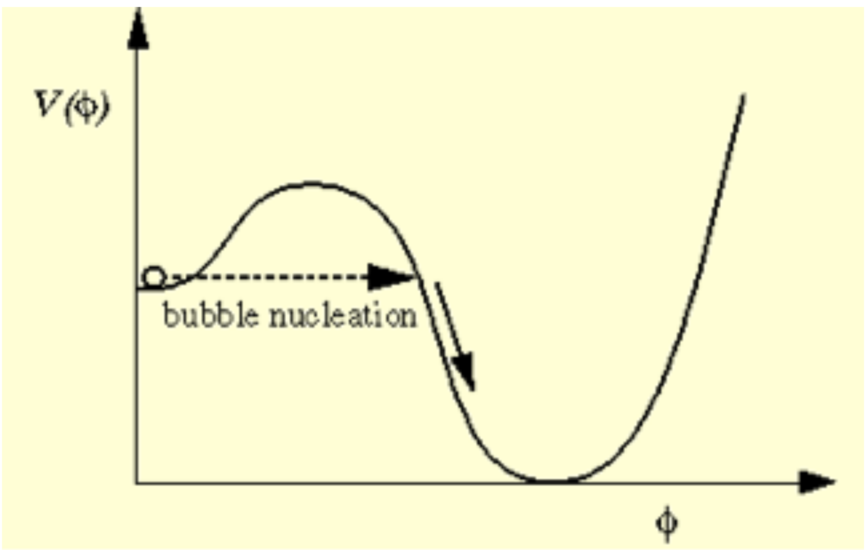


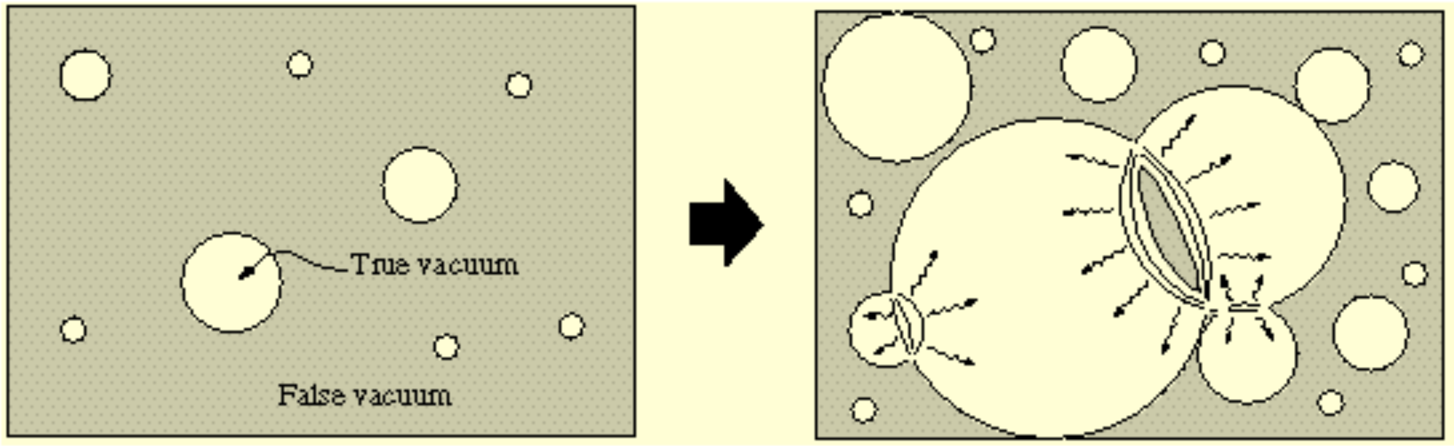
Small probability that loop will get into configuration where all dimensions lie within Schwarzschild radius (and hence collapse to from a PBH with mass of order the horizon mass at that time).

Probability is time independent, therefore PBHs have extended mass spectrum.

Bubble collisions Hawking

1st order phase transitions occur via the nucleation of bubbles.





PBHs can form when bubbles collide (but bubble formation rate must be fine tuned).

PBH mass is of order horizon mass at phase transition:

GUT scale: $\sim 10^3$ g

electroweak scale: $\sim 10^{28}$ g

QCD scale: $\sim 10^{32}$ g